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Recent results of simultaneous measurements of line electron density and poloidal field-induced Faraday rotation on the multichannel FIR interferometer/polarimeter on TFTR are presented. The procedures and results of the calibration are described in detail. The effects of various errors in the measurement, as well as the problem of cross-coupling laser beams, are studied.

INTRODUCTION

In earlier papers,[1,2] a multichord far-infrared (FIR) interferometer/polarimeter system on the TFTR tokamak was described. This paper presents the recent results of the simultaneous measurements of line electron density and Faraday rotation in TFTR plasmas. The propagation of FIR waves in the plasmas have also been investigated to ensure successful measurements of electron density and plasma current distributions in large tokamaks. Detailed mathematical analyses and experiments are presented.

EXPERIMENTS

The interferometer/polarimeter system on TFTR consists of a Michelson-type interferometer made from two cw 119 μm methanol lasers, optically pumped by a CO_2 laser. The beat frequency of the FIR lasers is usually adjusted to approximately 1 MHz by tuning the cavity length. The probing and reference beam are divided into ten channels by metallic meshes. The probing beams go through the plasma from bottom to the top and are reflected by the retro-reflectors. All optical components are mounted on a Diagnostic Support Structure totally isolated from the TFTR machine and supported on seismic isolators. The FIR laser beams are initially linearly polarized. A wire-grid polarizer is used as an analyzer to provide the

Faraday rotation signal. The analyzer is adjusted such that it passes the outgoing probing beam and reflects any rotated component of the return beam. This component is mixed with a portion of the reference beam, and is directed onto the polarimeter detector. Schottky diodes are utilized for all detectors. The output of the polarimeter detector is filtered, amplified, and fed into an envelope detection circuit. If the ellipticity of the polarization of the return beam is negligible, the output of the detection circuit is proportional to sin (θ_p), where θ_p is the Faraday rotation angle of the polarization vector, and is proportional to the line integral of electron density times the poloidal magnetic field along the double-path of the probing beam. Part of the beam from the reference laser is mixed first in the reference detector with a portion of the source laser, which is split off before passage through the plasma, and the remainder is guided to the signal detector to mix with part of the return beam. The outputs of both detectors are also filtered, amplified, and fed into a digital phase detection circuit to extract the phase shift produced by the electron density. Due to limited resources, only the outputs of the phase detectors are digitized for computer storage and processing (April 1985). The output of the envelope detection circuit is displayed on oscilloscopes for photographic recording (only one channel).

The interferometer/polarimeter system was routinely employed to study the ohmic- as well as neutral-beam-heated plasma discharges in the TFTR tokamak. Figure 1 shows the time-resolved traces of the line electron density and the Faraday rotation of a neutral-beam-heated plasma discharge. During this discharge, a solid hydrogen pellet was injected into the plasma at the time of approximately 2.4 seconds after the beginning of the discharge. The abrupt changes of density and Faraday rotation occur during a period of approximately 400 μs.

During the period of operation, sinusoidal oscillation of the Faraday rotation signal due to the cross coupling of the laser beams was observed occasionally (Fig. 2). Including the effect of the cross coupling, the output of the polarimeter detector, V_p, can be represented by the following expressions:

$$V_p = V_{po} \cos (\Delta\omega t + \phi_p)$$

$$V_{po} = KE_R[E_S^2 \sin^2 (\theta_p) + E_C^2 + 2E_SE_C \sin (\theta_p) \cos (\phi)]^{1/2}$$

where E_R and E_S are the fields of reference and probing beams respectively, K is the responsivity of the polarimeter detector, ϕ is the phase shift due to electron density, E_C is the field of the cross coupling beam, and ϕ_p is given by

$$\phi_p = \mathrm{Tan}^{-1}\left[\frac{E_S \,\mathrm{Sin}\,(\theta_p)\,\mathrm{Sin}\,(\phi)}{E_S \,\mathrm{Sin}\,(\theta_p)\,\mathrm{Cos}\,(\phi) + E_C}\right]$$

This relation can also be expressed graphically in Fig. 3. It can be seen in Figs. 2 and 3 that the amplitude of the oscillation is proportional to E_C, and the frequency is dependent on ϕ. Isolators have been successfully designed and tested to reduce the cross coupling of the laser beams, and the measurements on TFTR are under way.

ANALYSES AND DISCUSSIONS

An algorithm for the solution of the wave propagation equation has been developed and has been used to determine the polarization evolution on the Poincaré sphere. Computer codes have been utilized to calculate the ellipticity, ε, and the rotation angle of the vibrational ellipse, θ_p, of the polarization.

The parameters for TFTR are: major radius, R = 265 cm; minor radius, a = 85 cm; central electron density, $n_0 = 10^{14}/cm^3$; plasma current, I_p = 2.5 MA; toroidal field, B_T = 5.2 T; wavelength, λ = 119 μm (April 1985). In this case, the maximum θ_p is approximately 15° with a maximum ellipticity of 0.045 for double path of the beam. The output signals of the interferometer detector, V_i, and polarimeter detector, V_p, can be expressed by the following relations.

$$V_i = V_{io}\mathrm{Cos}(\theta_p)\left[1 + \varepsilon^2\mathrm{Tan}^2(\theta_p)\right]^{1/2}\mathrm{Cos}(\Delta\omega t + \phi + \psi_i)$$

$$V_p = V_{po}\mathrm{Sin}(\theta_p)\left[1 + \varepsilon^2\mathrm{Cot}^2(\theta_p)\right]^{1/2}\mathrm{Cos}(\Delta\omega t + \phi + \psi_p)$$

where V_{io} and V_{po} are the calibration constants for the interferometer and polarimeter, respectively, and ψ_i and ψ_p are given by

$$\psi_i = \mathrm{Tan}^{-1}[\varepsilon\,\mathrm{Tan}\,(\theta_p)] \qquad \psi_p = \mathrm{Tan}^{-1}[\varepsilon\,\mathrm{Cot}\,(\theta_p)]$$

It can be seen in the equations that both the amplitude and the phase of the signals depend on the ellipticity of the polarization which cannot be measured easily due to limitations on the experimental techniques. The error of density measurement due to neglecting of the ellipticity is very small (0.024 percent), and the error of the Faraday rotation measurement is approximately 1.7%. If the output signals of the interferometer and polarimeter detectors are fed into an analog multiplication circuit, the output of the circuit, V_{out}, is then given by

$$V_{out} = V_o\ (1 - \varepsilon^2)\ \mathrm{Sin}\ (2\ \theta_p)$$

The calibration constant V_o can be obtained by inserting a quarter wavelength Y-cut crystal quartz plate in the probing beam and measuring the value of the V_{out} without plasma in the chamber. It is interesting to note that the error of Faraday rotation measurement due to neglecting of ellipticity is reduced to approximately 0.2% for the plasma parameters of TFTR.

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[1]H. Park, D. K. Mansfield, L. C. Johnson, and C. H. Ma, Fifth Topical Conference on High Temperature Plasma Diagnostics, Tahoe City, California, September 16-20, 1984.

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FIGURE CAPTIONS

Figure 1. Time variations of the line electron density and the Faraday rotation measured by the multichord FIR interferometer/polarimeter system on TFTR tokamak. The abrupt changes of the line density and Faraday rotation are caused by the injection of a solid hydrogen pellet approximately 2.4 seconds after the beginning of the discharge.

Figure 2. Time variations of the line electron density and the Faraday rotation measured by the multichord FIR interferometer/polarimeter system on TFTR tokamak with strong cross coupling of FIR beams.

Figure 3. Graphical representation of the relation among the oscillation of the Faraday rotation signal (V_{po}), the responsivity of the polarimeter detector (K), Faraday rotation (θ_p), phase shift (ϕ), and the fields of the reference (E_R), probing (E_S), and cross coupling (E_C) beams.

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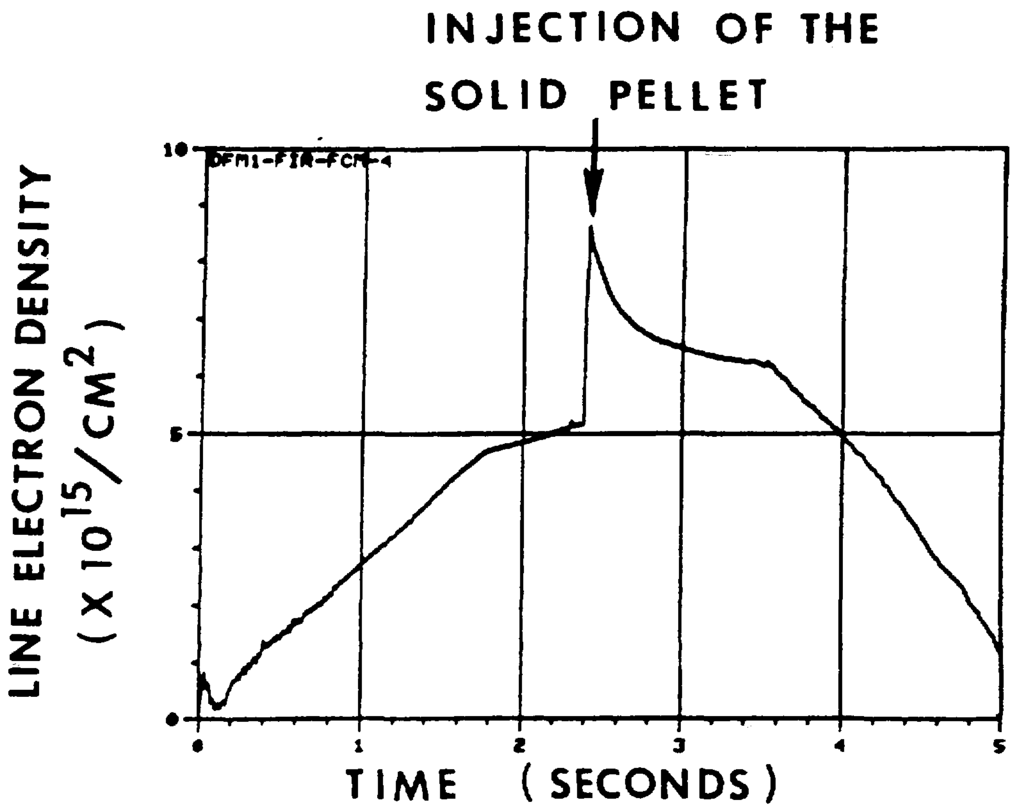

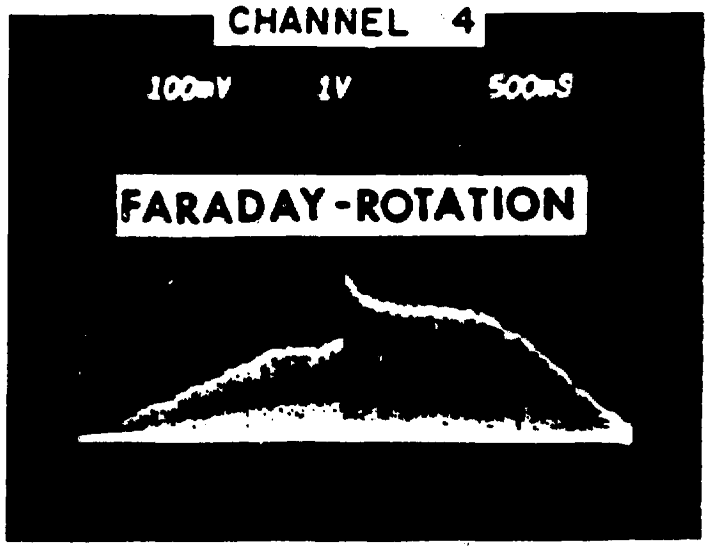

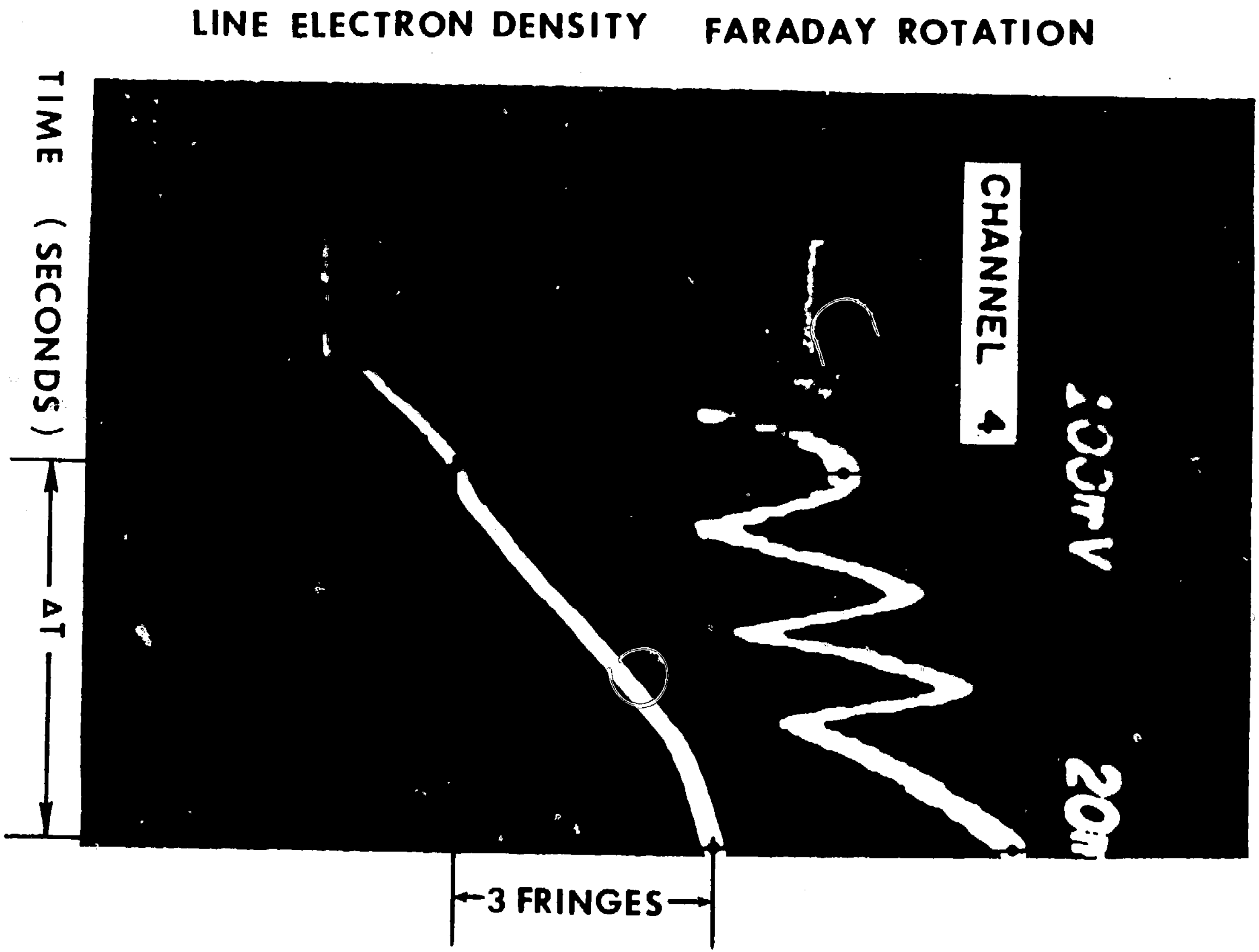

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